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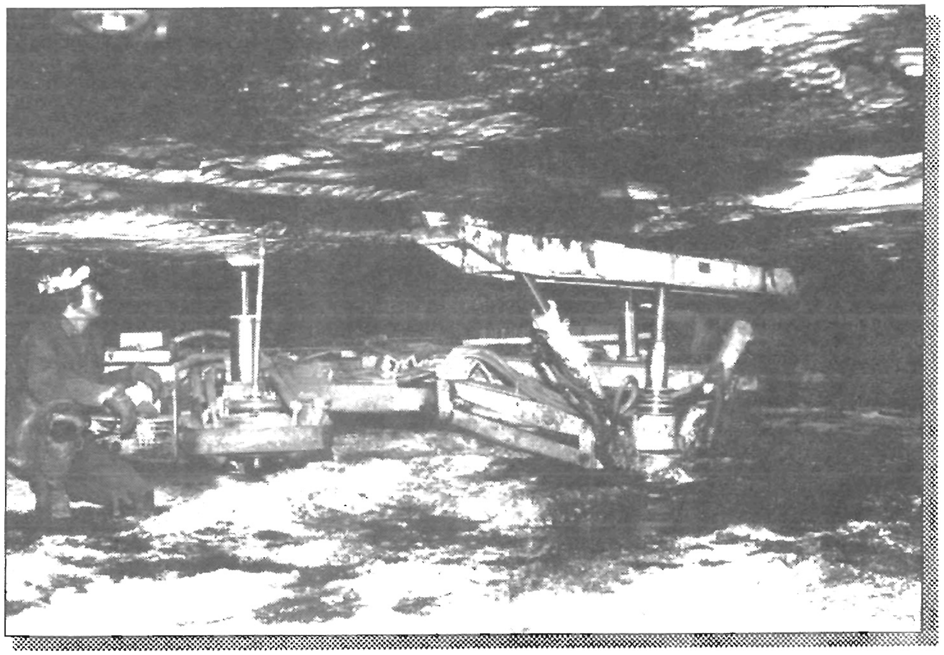
# Investigation of Optimum Thrust, Cutting Speed, and Water Pressure for Tungsten Carbide and Polycrystalline Diamond Compact Roof-Bolt Drill Bits





UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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***Cover: Roof bolter in action.***

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# Investigation of Optimum Thrust, Cutting Speed, and Water Pressure for Tungsten Carbide and Polycrystalline Diamond Compact Roof-Bolt Drill Bits

By Laxman S. Sundae, Thomas W. Smelser,
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UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea Lydia Graham, Director

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## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric

| | | | |
|---|---|---|---|
| cm | centimeter | L/min | liter per minute |
| cm/min | centimeter per minute | m/min | meter per minute |
| cm/s | centimeter per second | mm | millimeter |
| $g/cm^3$ | gram per cubic centimeter | MPa | megapascal |
| GPa | gigapascal | N | newton |
| J | joule | pct | percent |
| kg | kilogram | rpm | revolution per minute |
| $kg/mm^2$ | kilogram per square millimeter | s | second |
| kN | kilonewton | $\mu m$ | micrometer |
| kPa | kilopascal | °C | degree Celsius |

## OTHER ABBREVIATIONS AND ACRONYMS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| GE | General Electric | PDC | polycrystalline diamond compact |
| MSHA | Mine Safety and Health Administration | WC-Co | tungsten carbide |

# INVESTIGATION OF OPTIMUM THRUST, CUTTING SPEED, AND WATER PRESSURE FOR TUNGSTEN CARBIDE AND POLYCRYSTALLINE DIAMOND COMPACT ROOF-BOLT DRILL BITS

By Laxman S. Sundae,[1] Thomas W. Smelser,[2] and Wayne L. Howie[3]

## ABSTRACT

Laboratory tests were conducted at the U.S. Bureau of Mines to determine the effects of roof-bolt drilling parameters on penetration rate in sandstone using tungsten carbide alloy (WC-Co) and polycrystalline diamond compact (PDC) drill bits. During the tests, water pressure of 552 kPa was found to be adequate for removing the cuttings from the tops of drill holes. Test results show that for both types of bits, penetration rate increased when thrust was raised from 227 to 1,588 kg. When water pressure rose from 554±120 to 1,344±350 kPa, the effect on penetration rate was not significantly different. Conventional WC-Co bits became dull when one or two holes were drilled, after which the penetration rate dropped dramatically. Microscopic examination shows that the cutting edges of PDC bits also become somewhat dull, but at a much lesser rate than WC-Co tips. Microscopic examination also reveals that the wear mechanism of WC-Co and PDC bits is quite different, which may explain the longer life of the PDC bits.

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# INTRODUCTION

Roof bolting was introduced in American mines in early 1936 (*1*).[4] A British study shows that roof bolting costs about 66 pct less than any other roof support method (*2*). It is such an economical method that now it has been adopted as a roof support method in mines all over the world.

In 1968, the U.S. Bureau of Mines (USBM) estimated that 69 pct of the coal mined in the United States was mined under bolted roofs, which required 55 million roof bolts (*1*). Mine Safety and Health Administration (MSHA) estimates suggest that currently, more than 500 million bolts a year are used at a cost of $2.15 per bit, costing more than a billion dollars per year.[5] USBM research also shows that roof bolting, though relatively economical, remains a very expensive aspect of the mining industry (*3-4*).

In the past, to reduce roof support costs, the USBM directed its efforts toward minimizing drilling costs and comparing the performance of different types of commercial roof-bolt drill bits (*5-6*). However, in the last decade, these efforts have focused on developing emerging drilling and bit technologies (*3-4, 7-10*).

In 1991, the USBM tested PDC roof-bolt drill bits in nine coal mines located in the eastern and western United States. Results indicate that these bits have 200 to 600 times greater bit life compared to conventional WC-Co bits. Since the completion of these tests, more than 35 mines have started using PDC bits. Cost analysis of PDC and WC-Co bit sales, for 1993, indicates a saving of $1.5 million a year in bit costs alone, for the coal mining industry.[6]

During field testing, numerous attempts were made to find the optimum rotation speed, thrust, and water pressure for PDC bits. Observations using handheld equipment showed fluctuations in thrust and revolution per minute. Similarly, large variations in the water pressure were noted preventing accurate monitoring (*4*). The literature, reviewed in the appendix, offers no information concerning the effect of thrust and revolution per minute on performance and bit life for either WC-Co or PDC bits. Before improving the design of PDC bits or establishing standard operating procedures for their use, it is necessary to understand the interrelationship between operating parameters and penetration rate and bit life.

# EXPERIMENTAL DESIGN

The objective of this investigation was to determine optimum water pressure, thrust, and rotational speed (revolution per minute) for drilling with WC-Co and PDC roof-bolt drill bits. To this end, a semiautomated roof bolter, installed at the USBM, was used to conduct experiments in which these variables were examined.

Figure 1 shows the roof bolter used to conduct these experiments. This machinery was fitted with electronic sensors to measure thrust, revolution per minute, torque, and penetration rates. All test parameters were recorded continuously, while tests were being conducted.

## MECHANICAL PROPERTIES OF TEST MATERIALS

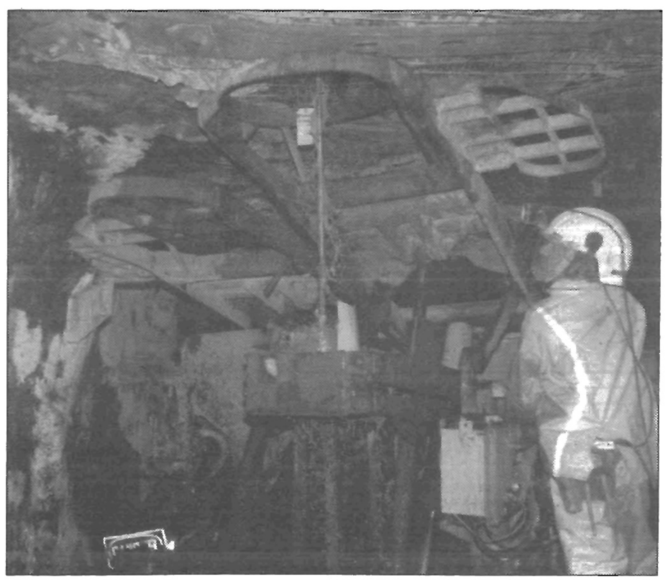
Mechanical properties of natural diamond, PDC, WC-Co, and 4340 steel are shown in table 1. This table shows that the thermal conductivity of PDC is seven times greater than that of WC-Co, while the hardness and the fracture toughness are 5.6 and 1.6 times greater than that of WC-Co. Test rock consisted of a pink sandstone containing 50 to 60 pct semi-round quartz particles. The grain size of quartz varied from 1 to 2 mm long, with sharp facets. The quartz particles were cemented together with small quantities of feldspar, calcite, muscovite, and other

[4]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

[5]Private communication from M. T. Heck, MSHA, 1992.

[6]Private communication from W. J. Brady, Brady Mining Tools, 1993.

*Figure 1*



*Roof bolter.*

**Table 1.—Physical properties of diamond, PDC, WC plus 6 pct Co, and 4340 steel[1]**

| Material properties | Natural diamond | PDC | WC plus 6 pct Co | 4340 steel |
|---|---|---|---|---|
| Density, g/cm$^3$ | 3.52 | 3.0-3.25 | 14.95 | 7.8 |
| Hardness-Knoop, kg/mm$^2$ | 6,000-9,000 | 5,000-8,000 | 1,475 | 558 |
| Young's modulus, MPa | 105-152 | 132 | 92 | 29 |
| Poisson's ratio | 0.1-0.29 | 0.2 | 0.22 | 0.3 |
| Tensile strength, kPa | NAp | NAp | 160 | 238 |
| Transverse rupture strength, kPa | NAp | 125-225 | 275 | NAp |
| Compression strength, kPa | 1,260 | 890 | 780 | 238 |
| Fracture toughness, $K_{IC}$ | 3.1 | 6.3 | 10.8 | 45.8 |
| Coefficient of thermal expansion at ($10^{-6}$/°C): | | | | |
| 25-100 °C | 1.34 | 1.5-3.8 | 4.3 | 11.2 |
| 25-200 °C | NAp | NAp | 4.7 | 12.4 |
| 25-400 °C | 2.29 | NAp | 5.0 | 13.6 |
| 25-600 °C | NAp | NAp | 5.4 | 14.3 |
| 25-800 °C | 3.14 | NAp | 5.6 | NAp |
| Thermal conductivity, 25 °C (watts/cm-°C) | 5-20 | 5.43 | 1.0 | 0.48 |

NAp Not applicable.
[1]Data provided by Smith International, Inc., Provo, UT.

minerals. Compressive strength of this sandstone was found to be 13,125 GPa.

## TEST BITS

The WC-Co bits used in this study were manufactured by Kennametal, Bedford, PA. These were made by sintering a mixture of 90 pct tungsten carbide and 10 pct cobalt at 1,800 to 2,400 °C. These inserts are brazed in a 4340 steel bit body at 1,200 to 1,400 °C. The cobalt content of inserts can be altered to match rock strength and hardness. The steel is relatively soft and does not materially contribute to bit life, but merely acts as a holder for WC-Co inserts.

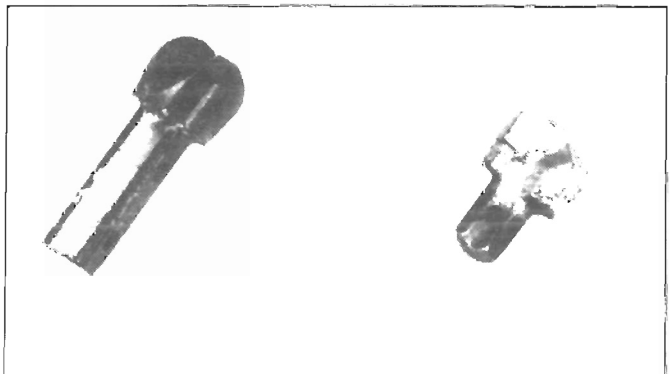
The synthetic diamonds used to manufacture PDC inserts for this investigation were made by General Electric (GE). PDC bit inserts or diamond compacts were sintered by MegaDiamond. Individual diamond particles from 1 to 6 $\mu$m are sintered at pressures and temperatures greater than 1 million psi and 1,400 °C. MegaDiamond mounts a diamond layer on two transitional layers containing different percentages of diamond and cobalt. The different layers in the diamond compacts absorb shock and minimize uneven thermal expansion of the WC-Co substrate and diamond layer. The roof-bolt drill bits were fabricated by Brady Mining Tools.

Each diamond compact or PDC insert was inspected individually by the X-ray diffraction method, and any PDC disk found to be defective was rejected. The roof-bolt drill bit design called for two half-disks mounted on alternate faces (figure 2). Each disk was brazed to the bit body, one at a time, using induction heating. Nothing is known about temperature gradients during the brazing process; it is believed that the first disk is subjected to higher temperatures than the second disk, and that accidental degradation of portions of the disk is possible. The diamond layer in PDC inserts is only 15 $\mu$m thick and may not be strong enough to withstand impact fracture caused by rocks that have a compressive strength greater than 206,843 kPa.

## TESTS PERFORMED

Experiments were performed using the test matrix shown in table 2. Thrust, water pressure, and bit type were independent variables while penetration rate, torque,

*Figure 2*



PDC roof bolt drill bit WC–Co roof bolt drill bit

*Test bits.*

and specific energy were dependent variables. Sixteen 61-cm-long holes were drilled in a sandstone block. All holes were placed 15 to 20 cm apart from each other to avoid the effects of anisotropy and heterogeneity of the block on test results.

The literature suggests that critical temperatures of 400 °C for WC-Co (*11*) and 750 °C (*12-14*) for PDC exist. However, during this testing, the possibility of temperature increases was eliminated by introducing water as a cooling, flushing, and lubricating agent. All tests were conducted at 450 rpm using 35 to 40 L/min of water. Thirty-five to ninety-five measurements of thrust, penetration rate, torque, and specific energy were made per hole. These measurements were made at intervals of approximately ½ s.

**Table 2.—Experimental design**

| Variables | WC-Co bit | PDC bits | | |
|---|---|---|---|---|
| | 2.54 cm | 2.64 cm | 3.5 cm | 2.45 cm |
| Water pressure, kPa | | | | |
| 590 ............ | X | X | X | X |
| 1,380 ........... | X | X | | |
| 2,100 ........... | X | X | | |
| Thrust, KN | | | | |
| 2.25 ............ | X | X | | |
| 5.00 ............ | X | X | | |
| 7.50 ............ | X | X | | |
| 10.00 ........... | X | X | | |
| 12.50 ........... | X | X | | |
| Rotational speed, rpm | | | | |
| 450 ............ | X | X | | |

## DISCUSSION OF TEST RESULTS

There is much less variability in the test results than anticipated for this type of test. This is because precautions were taken to minimize factors that can cause variability. The sandstone test block was fairly uniform; it did not contain any defects or flaws. Furthermore, the test holes were drilled to pass essentially through the same strata to reduce anisotropic effects at the measurement points.

### EFFECTS ON PENETRATION RATE

#### Thrust

Figure 3 shows that the penetration rate increased linearly with increased thrust for both WC-Co and PDC bits at each test condition and follows a linear relationship of Y = a + cX, where a (intercept) and c (slope) are constant, X = thrust, and Y = penetration rate. Penetration rates of 79, 107, 143, 189, and 229 cm/min were achieved for settings of 2.27, 4.54, 6.81, 9.08, and 11.35 kN of thrust, respectively. Figure 3 shows that for a worn-out PDC bit, once peak penetration rate is achieved, any further increase in thrust does not increase the penetration rate. The surface on a WC-Co bit becomes dull, suddenly; once that happens, no further penetration is achieved.

Test results in table 3 and figure 3 show that a 50-pct increase in thrust resulted in more than a 75-pct increase in penetration rates for 3.3-cm-diam PDC bits. Similarly, for a 2.54-cm-diam WC-Co bit, a 40-pct increase in thrust resulted in a 54-pct increase in penetration rate. These results show that in this test rock an increase in thrust is accompanied by a proportionately greater increase in penetration rate.

Considerable work has been done with percussive and rotary drills to determine the relationship between thrust and penetration rate (*15*). The cutting conditions for roof drilling are somewhat different from those for other modes of drilling, but these results are still in agreement with this experience (*15*).

This test series shows that thrust increases penetration rate. Increase in thrust makes a deeper indentation, and thereby increases depth of cut per revolution. Deeper cuts also increase the size of cuttings, which require less specific energy. Other factors that affect depth of indentation are bit tip angle, rake angle, and rock strength. Therefore, an increase in the penetration rate will differ according to cutting conditions. In soft shale, mudstone, siltstone, and clays it will be possible to achieve higher penetration rates with an increase in thrust, while in hard sandstone and dolomite, higher thrust may damage the sharp edges of bits.

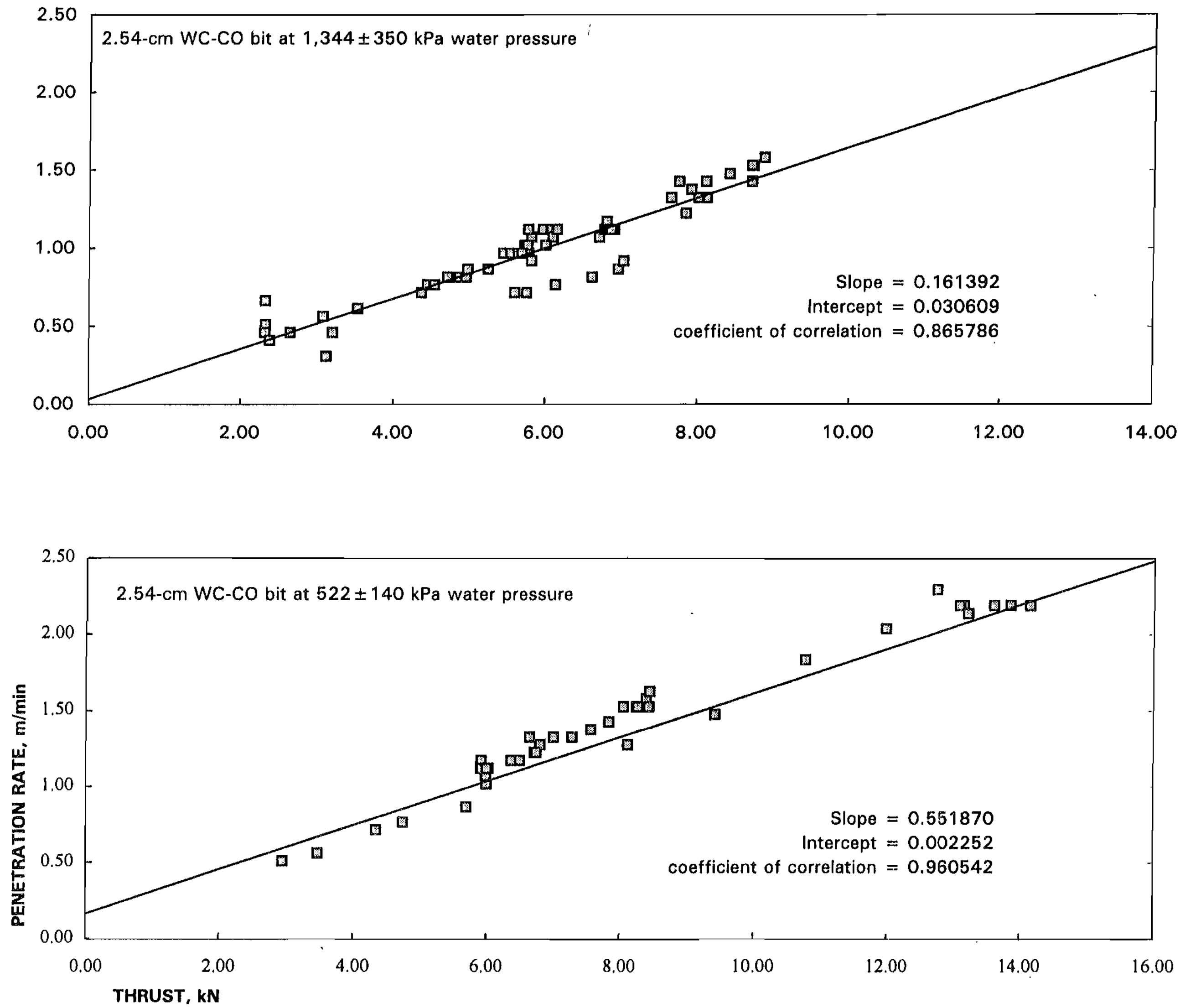
At present, it is not possible to determine optimum thrust because the roof bolter used in these tests is not capable of providing more than 15.88 kN of thrust.

#### Water Pressure

As previously mentioned, water acts as a cooling agent and flushes cuttings from the bit-rock contact area. Within certain limits, an increase in quantity of water and/or water pressure removes cuttings faster, keeps the bit tip clean, and promotes water circulation around the tip. Optimum water pressure promptly removes cuttings and greatly reduces regrinding of cuttings. Thus, within these narrow expectations, an increase in water pressure should show an increase in penetration rate and a decrease in specific energy.

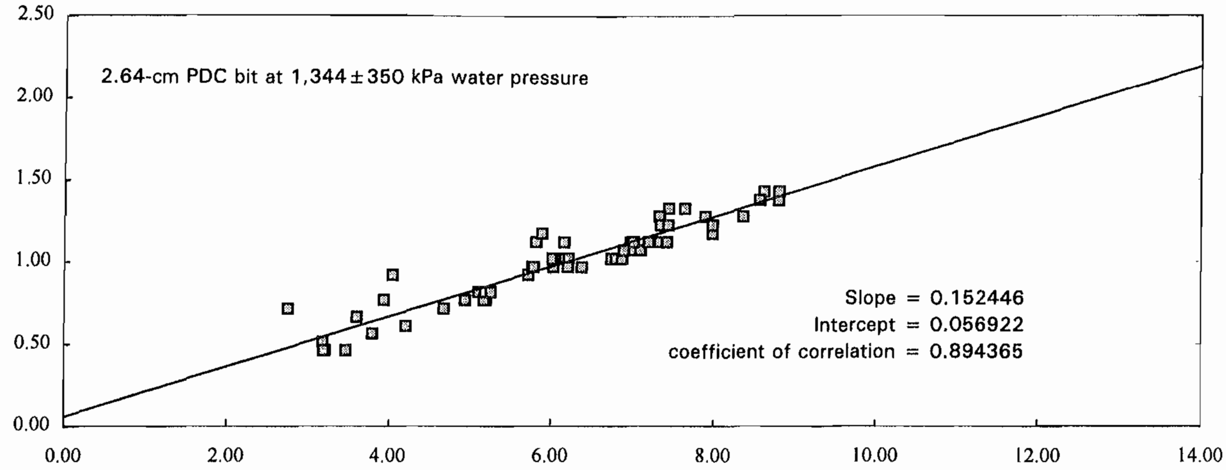
During these tests, when water pressure was increased from 552 to 1,379 kPa, the penetration rate increased noticeably and specific energy decreased for both the PDC and WC-Co bits (table 4 and figure 4 ). Physical observations made during the laboratory tests showed the bits

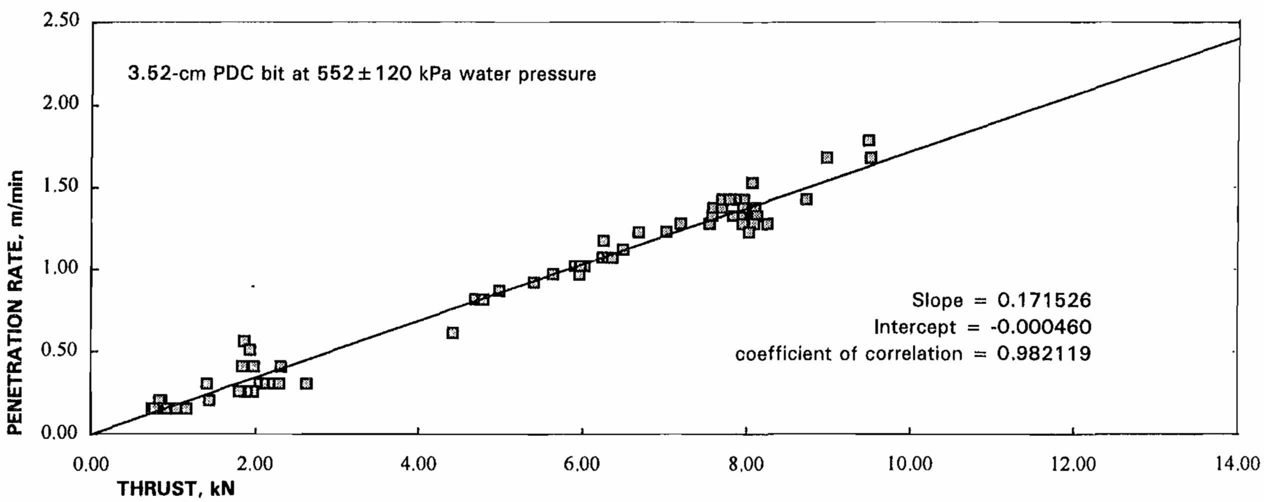
*Figure 3*




*Effect of thrust on penetration rate.*

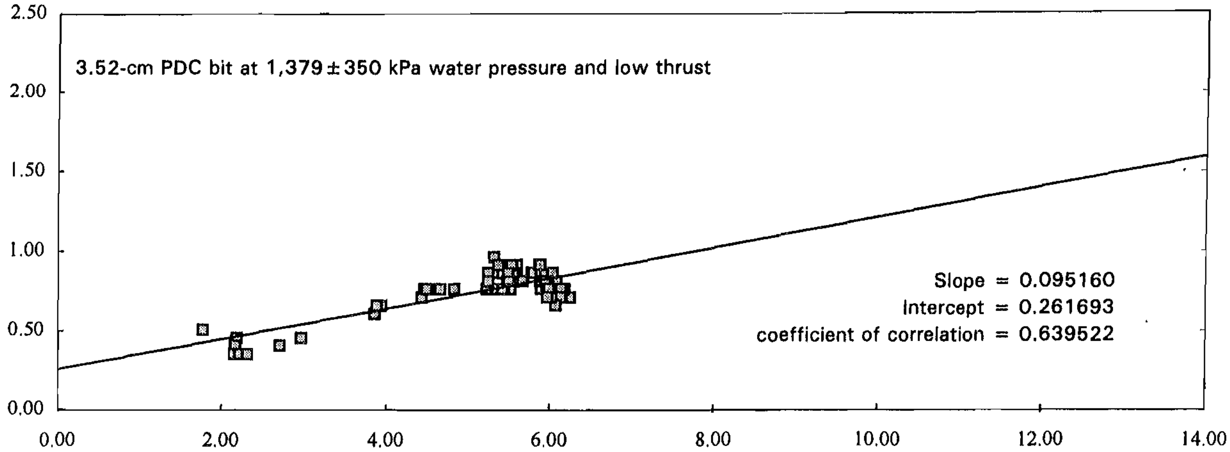
*Figure 3—Continued*

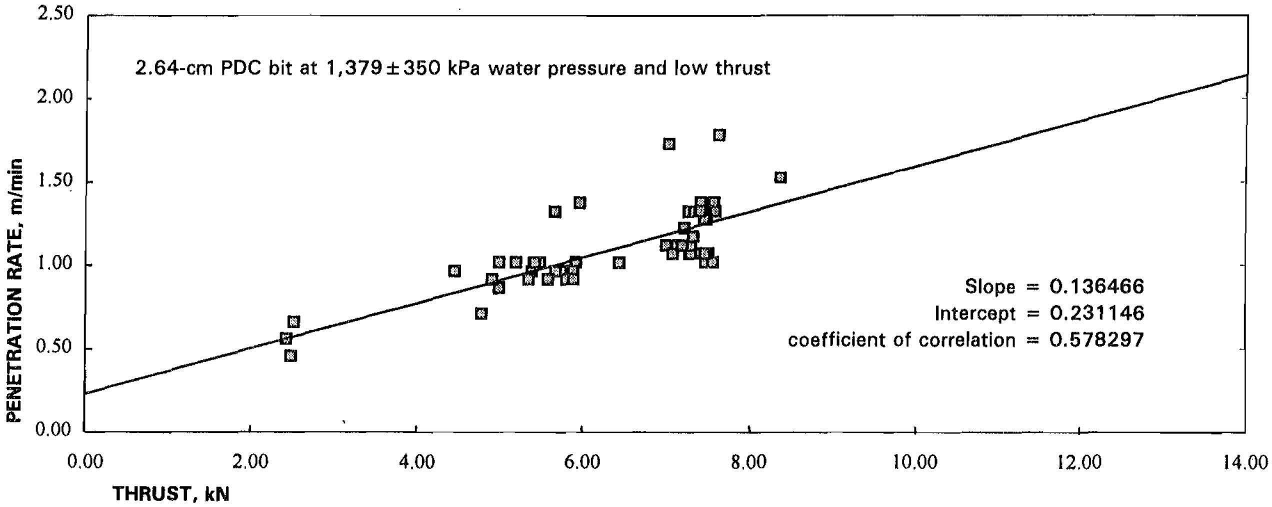



*Effect of thrust on penetration rate.*

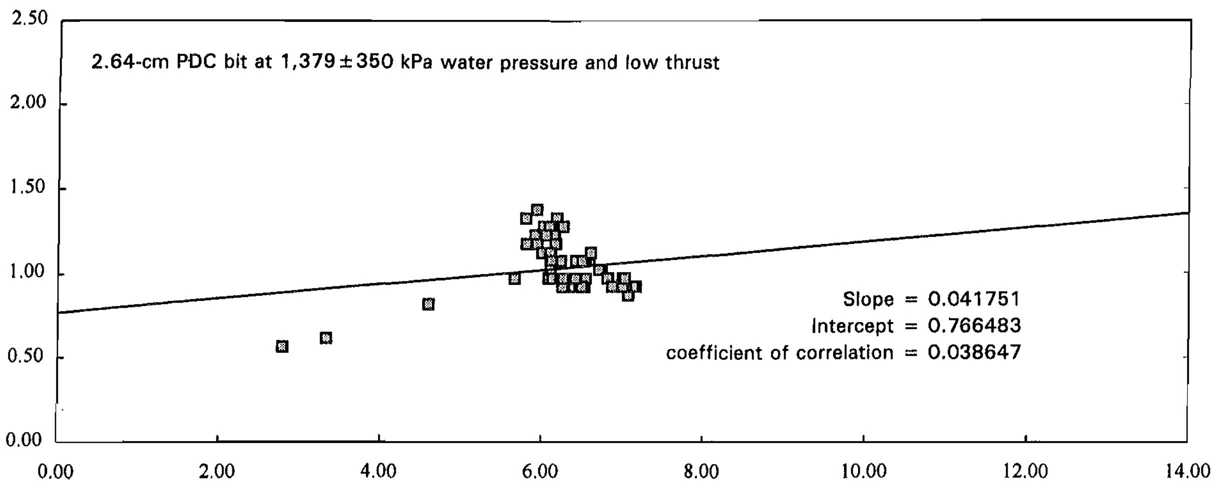
*Figure 3—Continued*

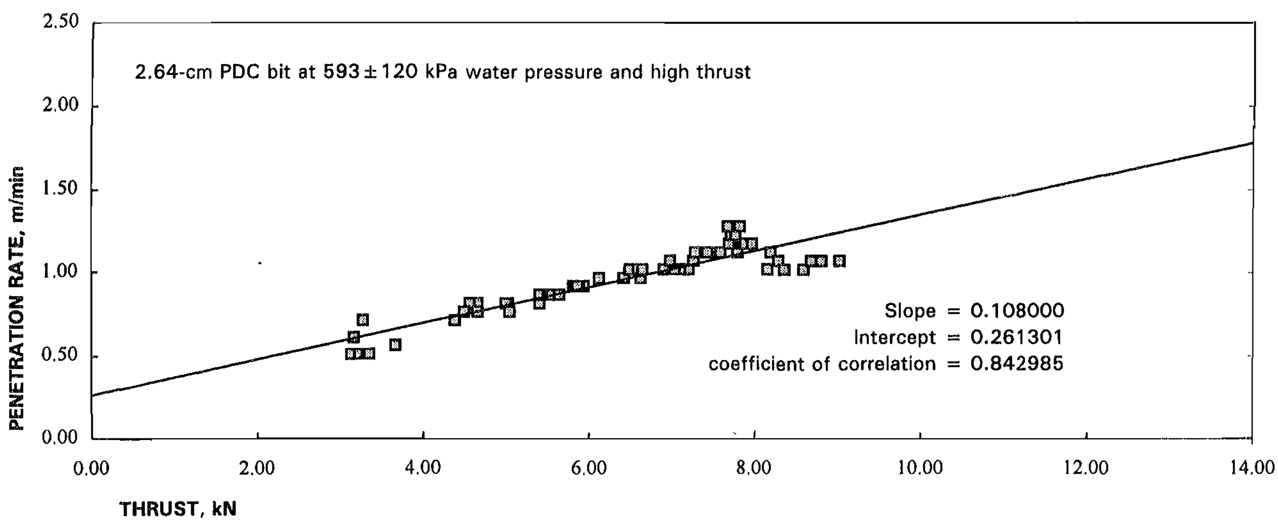



*Effect of thrust on penetration rate.*

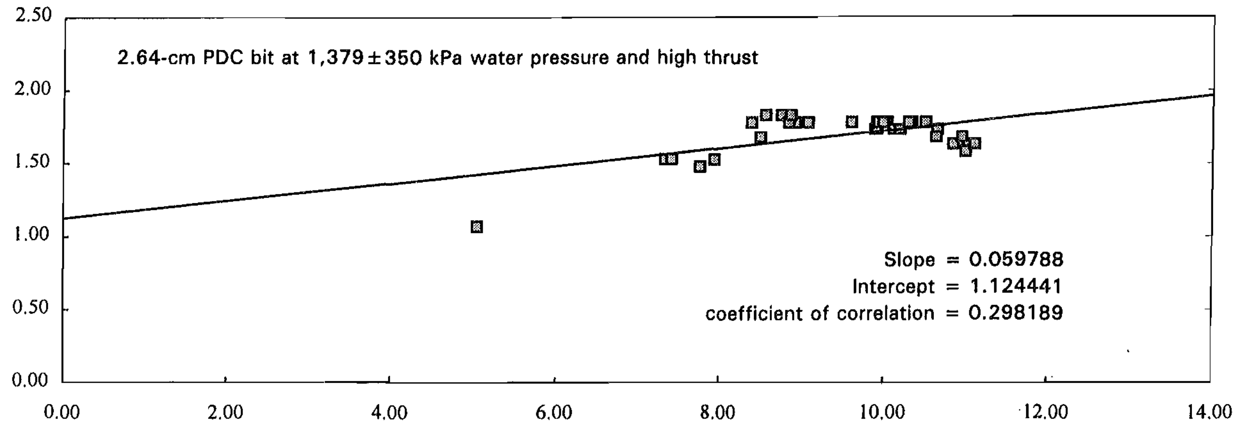
*Figure 3—Continued*

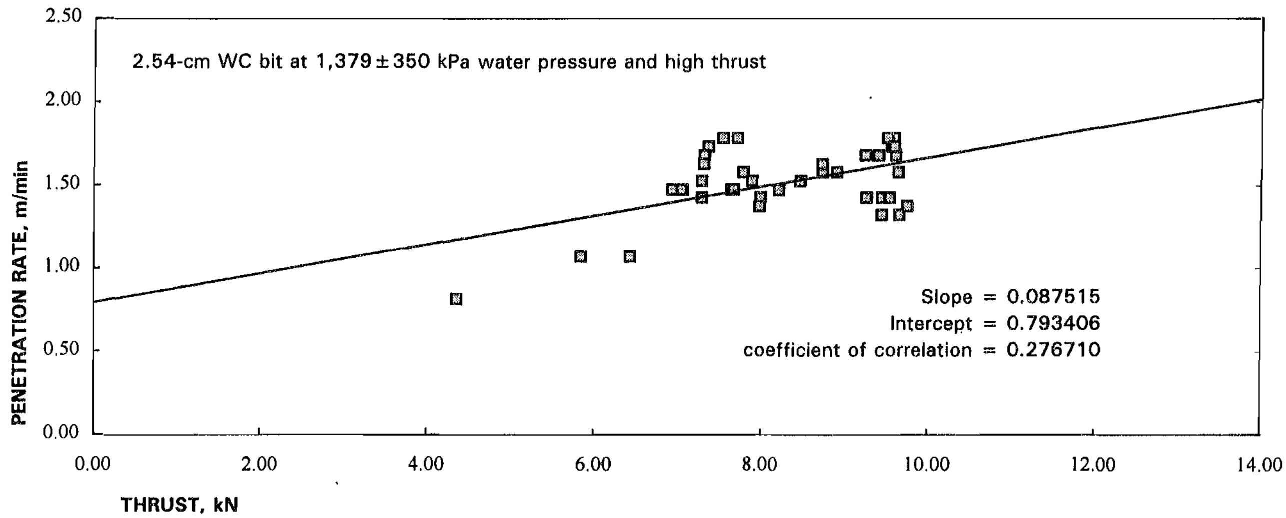



*Effect of thrust on penetration rate.*

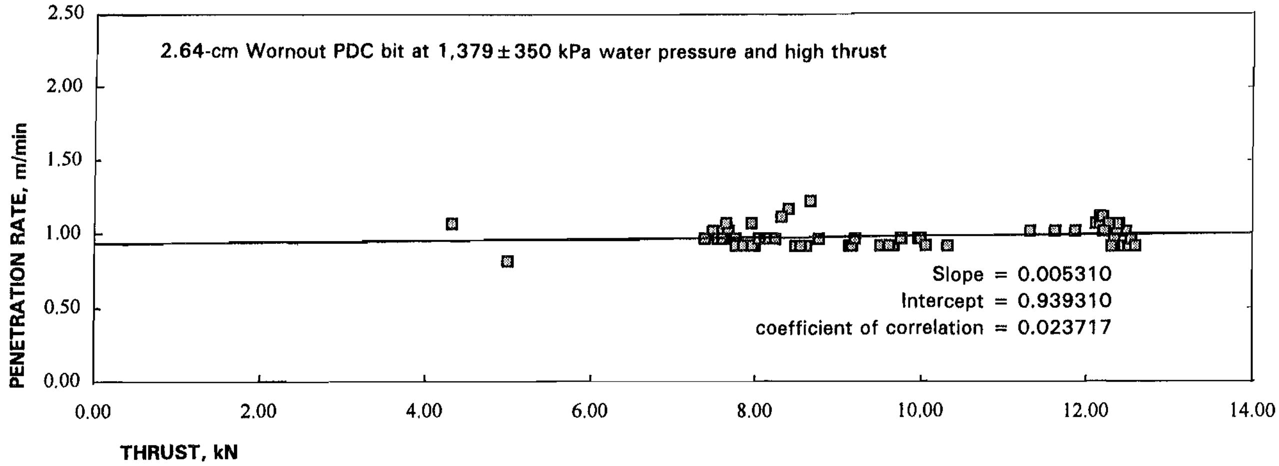
*Figure 3—Continued*




*Effect of thrust on penetration rate.*

*Figure 3—Continued*




*Effect of thrust on penetration rate.*

**Table 3.—Effect of increasing thrust on penetration rate, torque, and specific energy**

| Test variable, pressure | Thrust, N | Rotary speed, rpm[1] | Penetration rate, m/min | Torque, J | Specific energy, J |
|---|---|---|---|---|---|
| | | 2.64-cm PDC BIT, 551.6-kPa WATER PRESSURE | | | |
| Low thrust: | | | | | |
| Mean ........ | 6,366.75 | 433.00 | 0.95 | 29.20 | 34,537.77 |
| SD .......... | 1,619.63 | 2.00 | 0.19 | 7.38 | 3,310.71 |
| High thrust: | | | | | |
| Mean ........ | 9,521.33 | 424.59 | 1.69 | 52.23 | 35,540.15 |
| SD .......... | 1,328.81 | 1.93 | 0.15 | 6.81 | 3,371.06 |
| | | 2.54-cm WC-Co BIT, 1,379-kPa WATER PRESSURE | | | |
| Low thrust: | | | | | |
| Mean ........ | 5,891.24 | 442.60 | 0.98 | 31.94 | 39,299.12 |
| SD .......... | 1,781.59 | 49.54 | 0.30 | 6.97 | 8,518.75 |
| High thrust: | | | | | |
| Mean ........ | 8,232.73 | 428.12 | 1.51 | 33.46 | 26,455.62 |
| SD .......... | 1,244.12 | 1.25 | 0.20 | 4.23 | 2,782.20 |

SD Standard deviation.
[1]Set speed was 440 rpm.

were cool to the touch both at 552 and 1,379 kPa. Occasionally, at each water pressure, clay in the partings between the sandstone layers was sticky and molded around portions of the bit tips.

The linear correlation between thrust and penetration rates at 552 kPa water pressure suggests that optimum removal of cuttings was taking place at the top of the hole (figure 3). These results lend credence to the theory of perfect cleaning, which says that penetration rate is directly proportional to increase in thrust or rotational speed (*16*).

Gains in penetration rate and reductions in specific energy due to increase in water pressure from 552 to 1,379 kPa were less than expected; therefore, no tests were conducted at 2,068 kPa water pressures as originally contemplated. Test results suggest that 35 to 40 L/min of water at 552 kPa pressure is also more than adequate to flush out cuttings, and keep the bit body and tip cool and clean to avoid thermal degradation of both PDC and WC-Co inserts. However, 1,379 kPa water pressure is considered a greater safeguard against fluctuations in line pressure that can lead to bit tips overheating.

## Bit Diameter

At present, 2.54- to 4.13-cm-diam bits are used in coal mines to drill holes for installing roof bolts. In the past, it was not possible to compare the performance of different sizes of WC-Co bits because these bits became dull even when conducting tests. Therefore, nothing is known about the effects of bit diameter on penetration rate and other dependable variables. Since PDC bits do not suffer rapid wear, it was decided to compare the performance of two PDC bits having 2.64- and 3.52-cm diam. Two tests were conducted and more than 200 measurements were made to determine the effect of bit diameter on bit performance. The test results (table 5 and figure 5) show that 2.64-cm-diam bits require 69 pct less specific energy and cut 33 pct faster.

## NEW AND WORNOUT PDC BITS

Past research (*4*) and the USBM field tests (*5*) show that the cutting edge of a PDC bit remains sharp and penetrates the rock at the same rate during its entire cutting life. Several measurements were conducted on 2.46-cm worn and 2.64-cm new bits to investigate this. Test results (table 6 and figure 6 *A*, *B*, and *C*) show that for the same penetration rate, the wornout PDC bit requires 55 pct more thrust and consumes 2.6 times more energy toward the end of its life. Eventually, as the bit reaches the end of its life, it drills a smaller hole with somewhat lower penetration rate. If the thrust is not increased, the penetration rate will decrease. In these tests, the decrease in penetration rate was quite small because of automatic increases in thrust. It is possible that during field tests the penetration rate also decreased slightly because of dulling of the PDC insert, but this decrease was so small that it went undetected.

**Table 4.—Effect of increasing water pressure on test variables**

| Test variable | Thrust, N | Rotary speed, rpm[1] | Penetration rate, m/min | Torque, J | Specific energy, J |
|---|---|---|---|---|---|
| | | 2.64-cm PDC BIT | | | |
| 551.6 kPa: | | | | | |
| Mean ........ | 6,173.52 | 435.75 | 1.00 | 41.41 | 47,507.00 |
| SD .......... | 1,593.12 | 2.30 | 0.26 | 8.60 | 5,188.30 |
| 1,379 kPa: | | | | | |
| Mean ........ | 8,066.86 | 440.16 | 1.41 | 39.29 | 34,468.09 |
| SD .......... | 2,940.13 | 2.17 | 0.46 | 8.49 | 4,714.47 |
| | | 2.54-cm WC-Co BIT | | | |
| 551.6 kPa: | | | | | |
| Mean ........ | 6,366.75 | 433.00 | 0.95 | 29.20 | 34,537.77 |
| SD .......... | 1,619.63 | 2.00 | 0.19 | 7.38 | 3,310.71 |
| 1,379 kPa: | | | | | |
| Mean ........ | 6,270.36 | 434.98 | 1.03 | 29.54 | 33,156.71 |
| SD .......... | 742.94 | 1.02 | 0.16 | 3.47 | 3,447.58 |

SD Standard deviation.
[1]Set speed was 440 rpm.

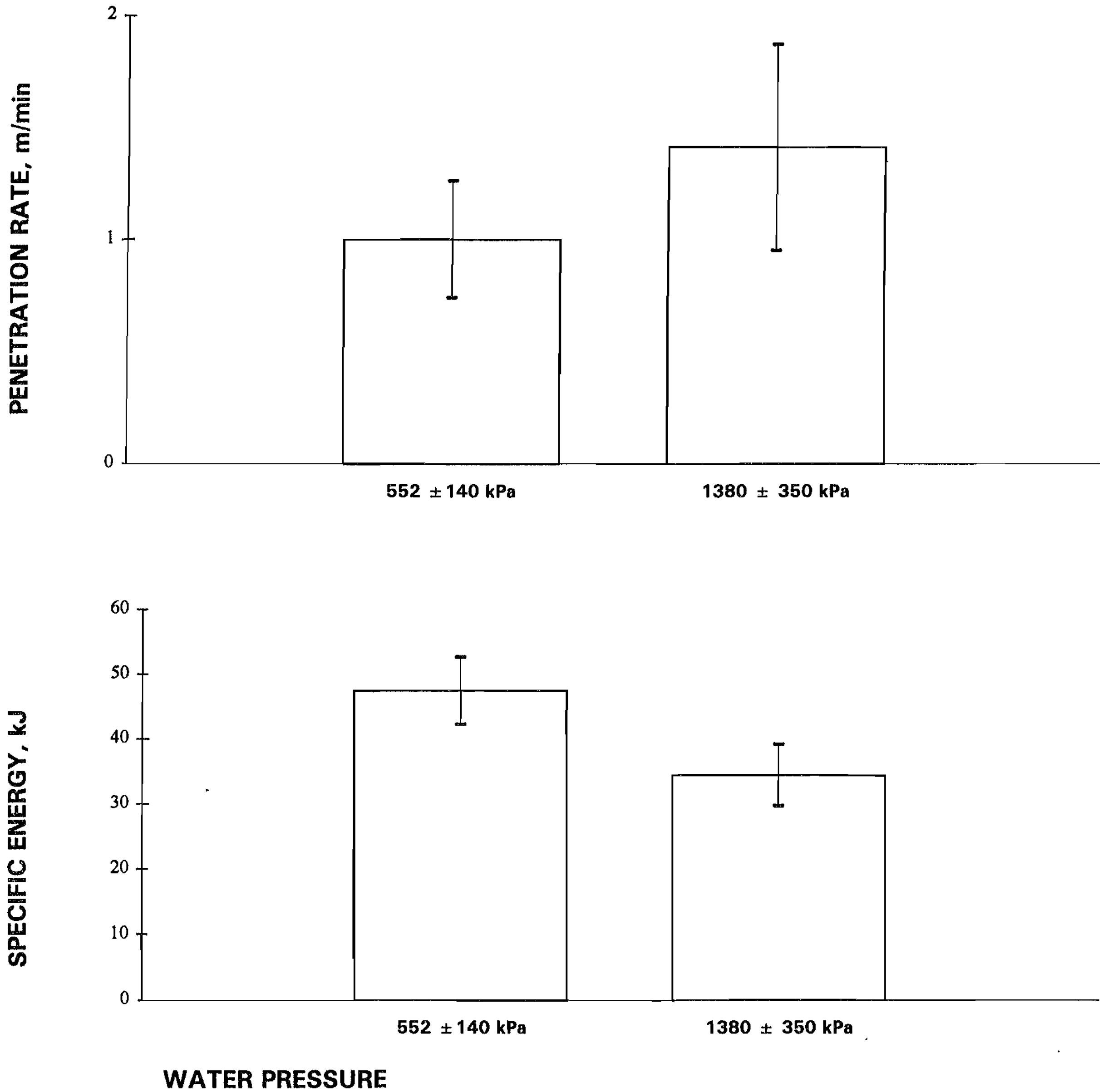
**Table 5.—Two tests for comparison of performance of 2.64- and 3.5-cm-diameter PDC bits**

**(At 1,379 kPa water pressure)**

| Test variable | Thrust, N | Rotary speed,[1] rpm | Penetration rate, m/min | Torque, J | Specific energy, J |
|---|---|---|---|---|---|
| 2.64-cm bit: | | | | | |
| Mean ........ | 6,173.52 | 435.75 | 1.00 | 41.41 | 47,507.00 |
| SD .......... | 1,593.12 | 2.30 | 0.26 | 8.60 | 5,188.30 |
| 3.5-cm bit: | | | | | |
| Mean ........ | 4,373.25 | 332.36 | 0.75 | 43.01 | 50,905.35 |
| SD .......... | 3,055.74 | 136.45 | 0.53 | 27.55 | 21,122.17 |
| 2.64-cm bit: | | | | | |
| Mean ........ | 6,334.24 | 439.24 | 1.09 | 44.55 | 46,879.88 |
| SD .......... | 1,330.01 | 1.71 | 0.24 | 6.56 | 4,774.17 |
| 3.5-cm bit: | | | | | |
| Mean ........ | 5,331.43 | 439.65 | 0.77 | 50.61 | 73,593.23 |
| SD .......... | 1,083.85 | 1.35 | 0.13 | 6.29 | 6,615.22 |

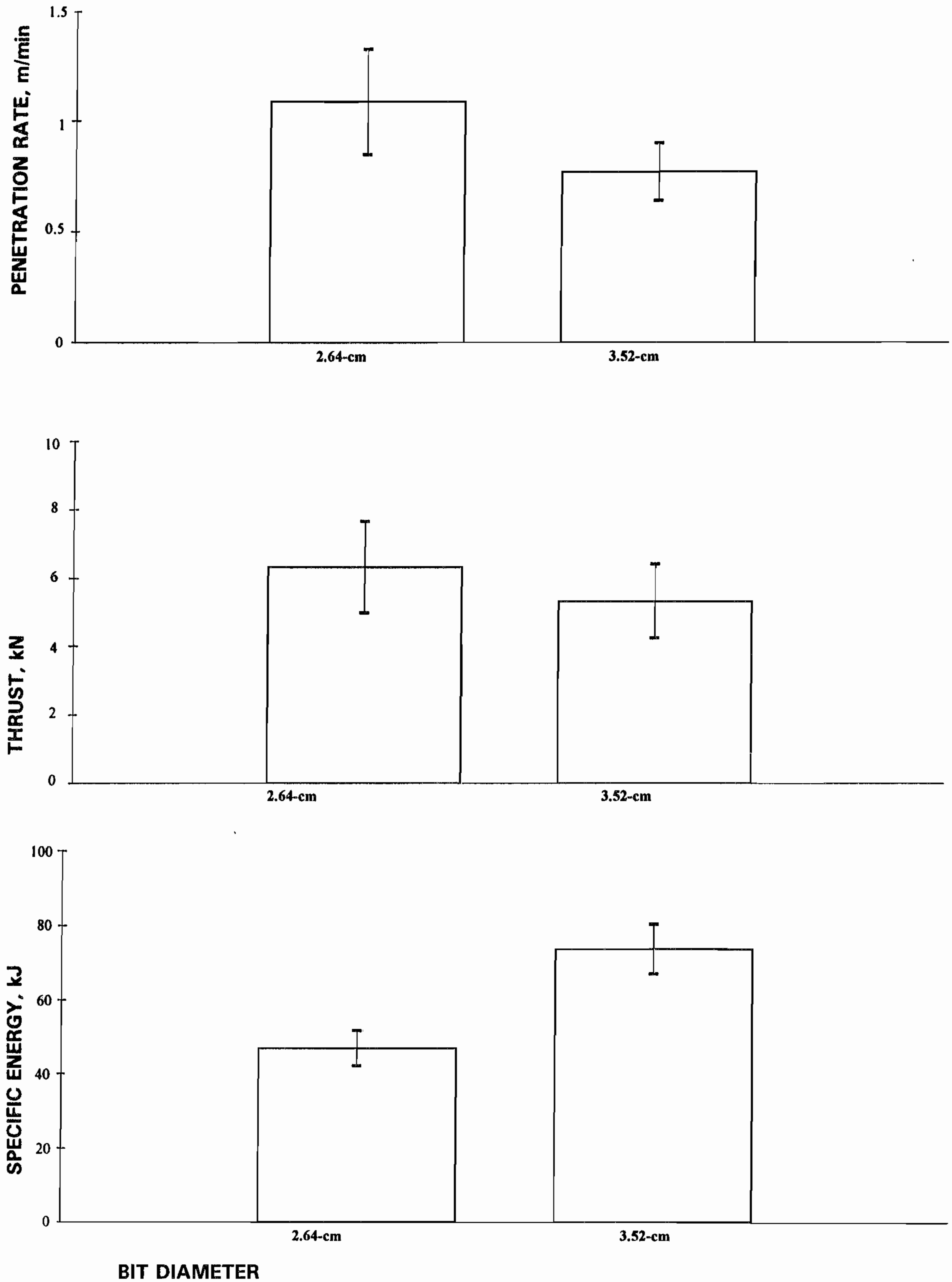
SD Standard deviation.
[1]Set speed was 440 rpm.

*Figure 4*




*Effect of increasing water pressure on penetration rate and specific energy for 2.64-cm WC-Co bit.*

*Figure 5*




*Effect of increasing bit diameter on penetration rate, thrust, and specific energy.*

Table 6.—Comparison of new versus wornout PDC bits, 1,379 kPa, 440 rpm

| Test variable | Thrust, N | Rotary speed,[1] rpm | Penetration rate, m/min | Torque, J | Specific energy, J |
|---|---|---|---|---|---|
| New 2.64-cm bit: | | | | | |
| Mean . . . . . . . . | 6,366.75 | 433.00 | 0.95 | 29.20 | 34,537.77 |
| SD . . . . . . . . . . | 1,619.63 | 2.00 | 0.19 | 7.38 | 3,310.71 |
| Worn-out 2.46-cm bit: | | | | | |
| Mean . . . . . . . . | 9,923.71 | 427.22 | 0.98 | 82.43 | 91,047.38 |
| SD . . . . . . . . . . | 2,150.44 | 3.08 | 0.07 | 12.30 | 12,524.25 |

SD Standard deviation.
[1]Set speed was 440 rpm.

## MICROSCOPIC ANALYSIS OF BIT WEAR

### Bit Wear Categories

PDC bit wear has been defined as microscopic and macroscopic degradation that reduces bit life by removing or fracturing material at the outer surface (*17*). In the past 10 years, a few investigators have studied the wear mechanism of PDC bits and have classified bit wear into four categories: (1) smooth, (2) microchipping, (3) gross fracturing, and (4) delamination at the interface of PDC and WC-Co substrate (*18*).

Figures 7 and 8 illustrate the wear mechanism of WC-Co and PDC inserts after completion of this study. These photographs were magnified eight times to show the details of fracture initiation on the cutting edge of bit tips. The WC-Co bit had a 75° tip angle and was mounted at a 0° rake and 15° clearance angle and the PDC bit had an 85° tip angle, and it was mounted at a plus 23° rake and minus 5° clearance angle. In all probability, the rake and clearance angles had some effect on the fracture and wear mechanism, but it was not possible to quantify this effect.

### WC-Co Bits

Figure 7 shows fracture patterns at the end of the WC-Co's cutting edges after drilling only one 61-cm-deep hole in medium-hard sandstone. This photograph suggests that the bit wear started at the beginning and gradually continued with bit use. Test results show that for sandstone, 552 to 1,379 kPa water pressure, 11.34 kN thrust, and 440 rpm are optimum parameters for the WC-Co bit. Any additional increase in thrust or revolution per minute will enhance the rate of destruction of the cutting edges of WC-Co bits.

The WC-Co tools have been in use for the past 5 decades and the tool design has been perfected. The WC-Co inserts are fitted well in a 4340 steel bit body. The bit body, unlike the PDC body, does not rub against the interior wall of the drill hole, and the brazing never causes delamination or bit failure due to snug fit of the WC-Co insert. Bit failure is simply caused by the abrasion of the WC-Co inserts against quartz particles or gross fracture when the bit tip impacts high strength roof rocks. In roof rock containing limestone, shale, and/or sandstone having compressive strength greater than 103,421 kPa, bit tip damage is caused by impact fracture or overheating of bit tips and bodies.

Under identical test conditions, the wear mechanism for WC-Co and PDC bits is quite different. At 13.61 kN thrust and 450 rpm, microchipping of the WC-Co insert takes place on the cutting edges of bits. After this, major chips will break off.

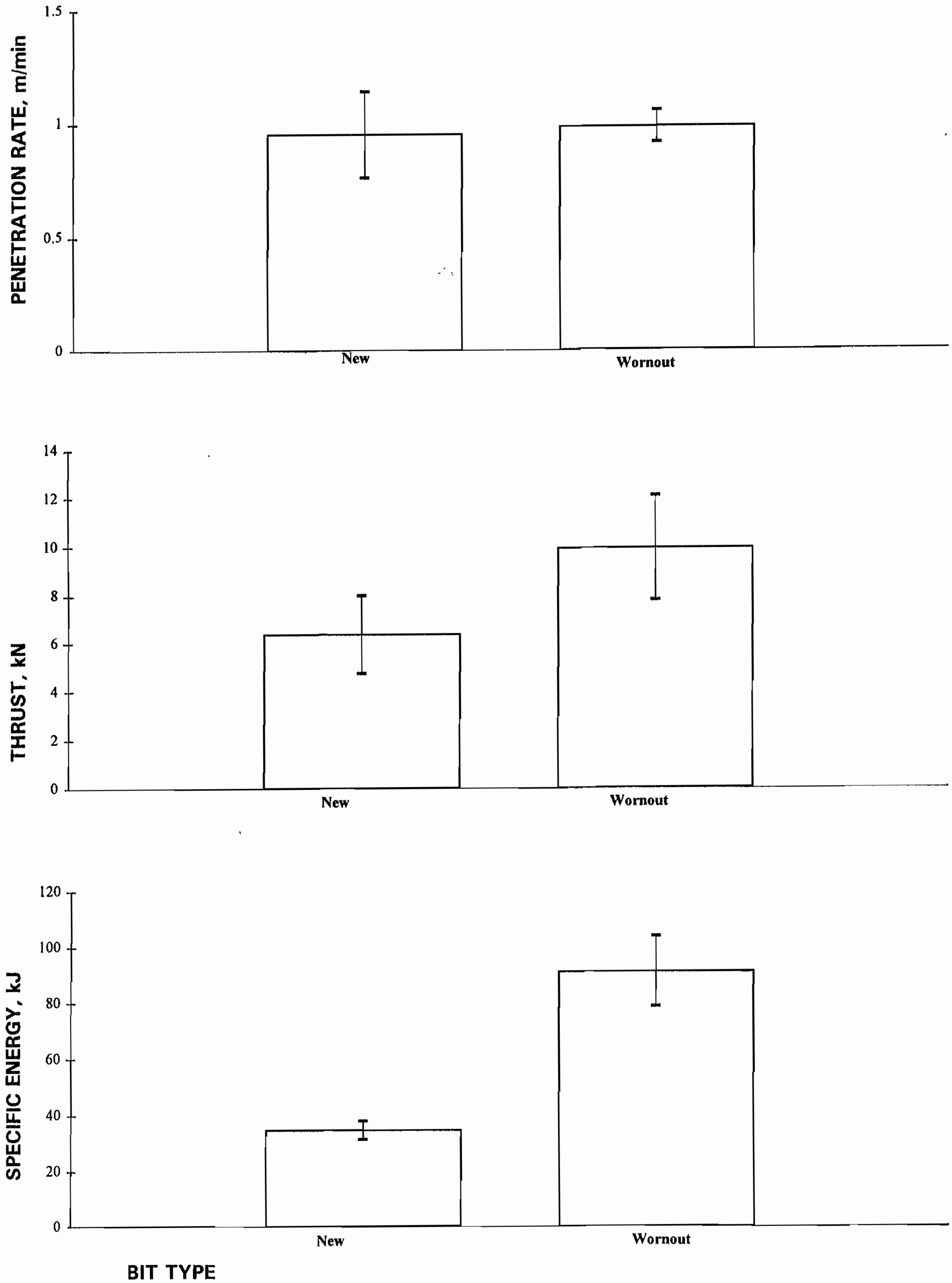
### PDC Bits

In comparison to the WC-Co inserts, the PDC inserts are relatively stronger, and under these test conditions the bit wear was limited to microscopic abrasion and gradual reduction in bit diameter. The diamond to diamond adhesion is very strong, so throughout its life the cutting edge of the PDC bit remains relatively sharp. Occasionally, some clay was found around the bit tip, but it apparently did not cause any damage to the bit tip or body. During laboratory testing, no microchipping action took place.

Figure 8 shows the PDC bit after drilling seven holes. When one examines this bit with the naked eye it appears that the diamonds are in place and some polishing effect has taken place on the disk apex. This type of wear has been noticed by other researchers (*18*). It suggests that gradual wear starts taking place as soon as the bit is put to use. Figure 8 is a photograph of the cutting edge magnified eight times, and it shows that a few diamond particles have been plucked from the cutting edge of the PDC insert.

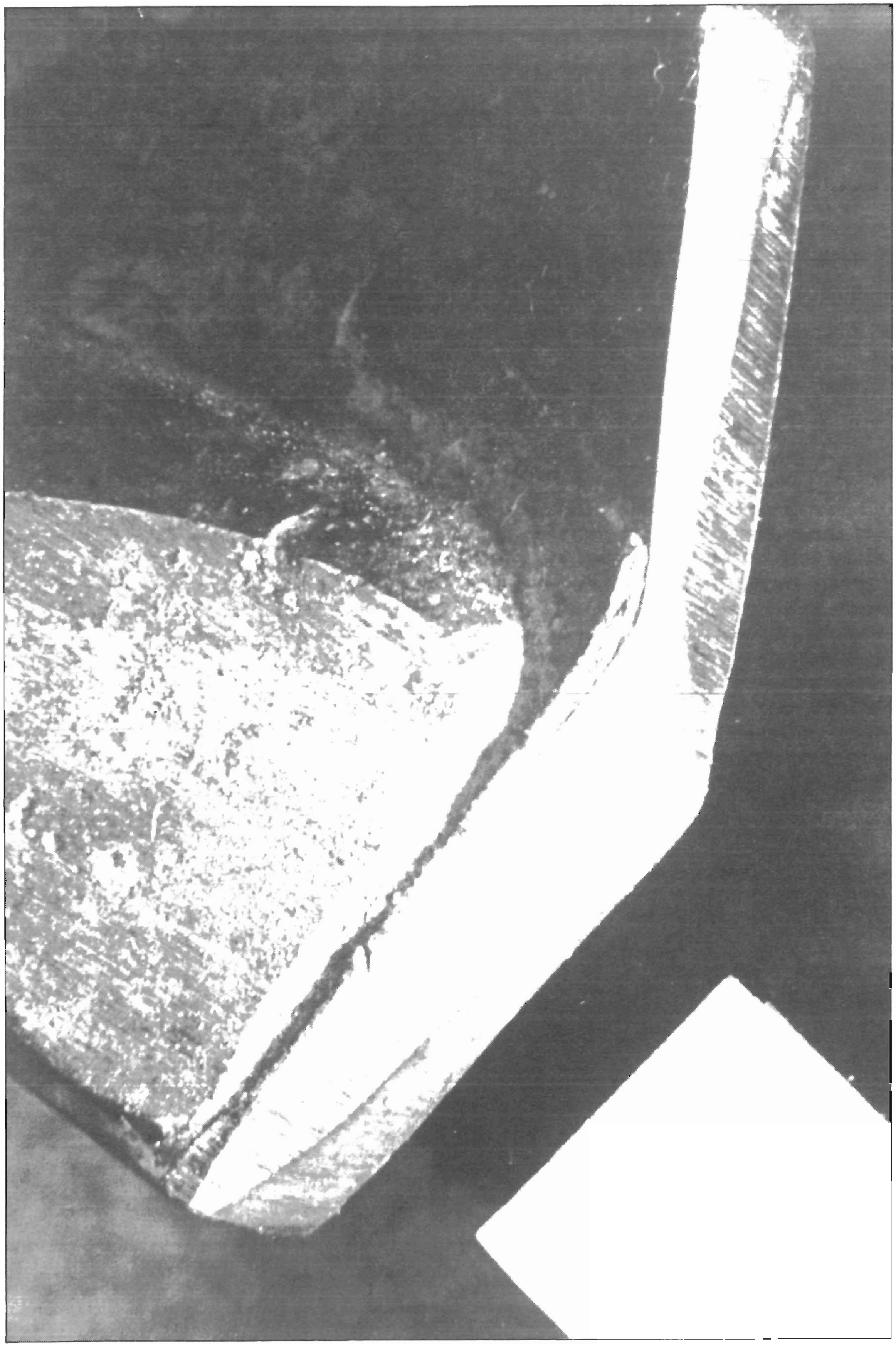
There is a significant difference between the wear patterns of WC-Co and PDC inserts (figures 7 and 8). With WC-Co inserts, clumps of WC-Co particles fracture along their boundaries, especially at the edges, while with PDC inserts the diamond particles are plucked (from what

*Figure 6*



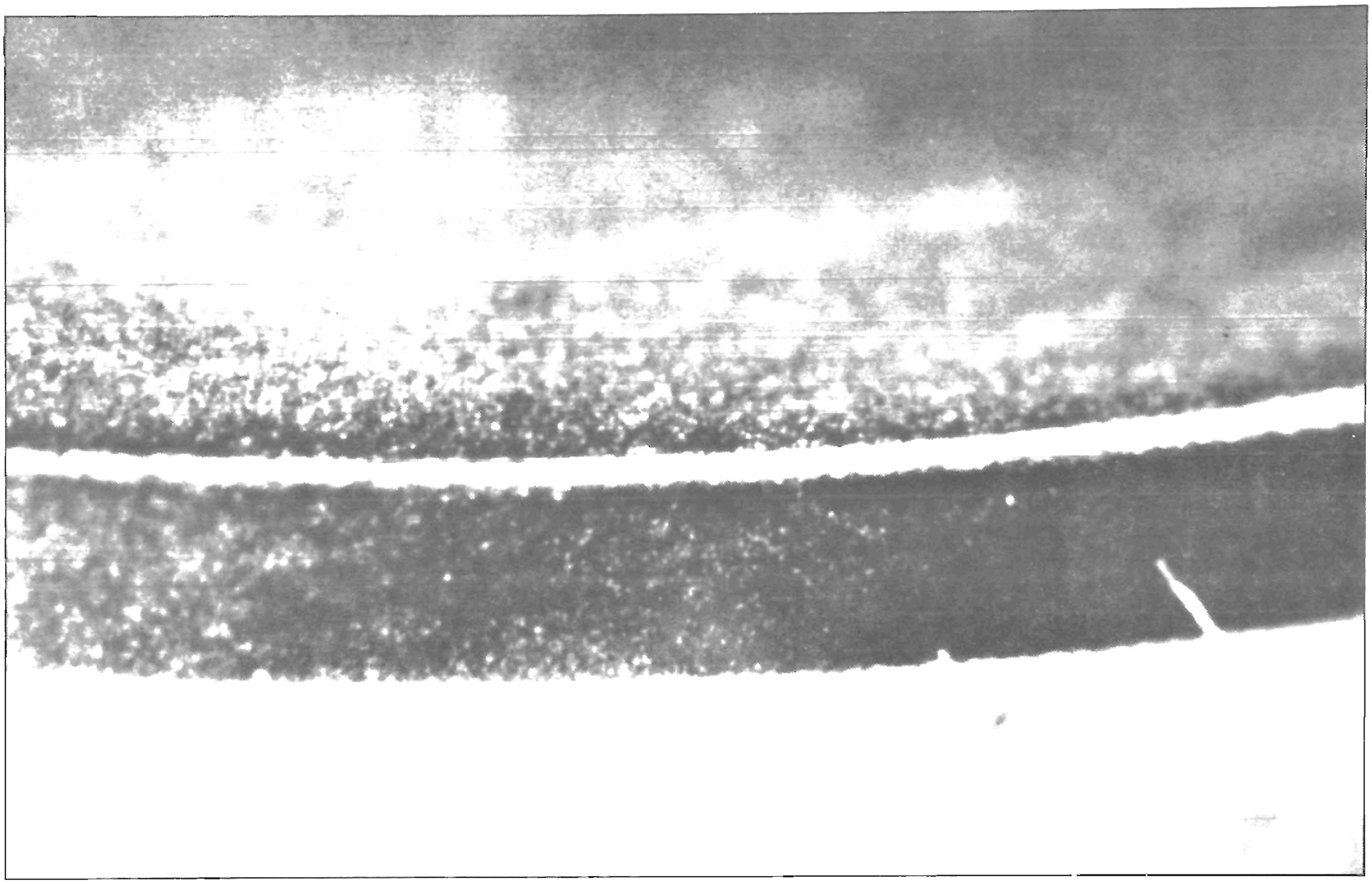

*Effect of new and wornout 2.64-cm diameter PDC bit on penetration rate, thrust, and specific energy.*

Figure 7



*Abrasion of cutting edge of WC-Co insert after drilling a 61-cm hole (8x).*

*Figure 8*



*Abrasion of cutting edge of PDC bit after drilling seven 61-cm holes (8x).*

appears to be a polished surface), one at a time, without disturbing those around them.

A review of the literature suggests that if the bits are operating at 30 pct of their fracture toughness, then damage to cutting edges would be absent (*19-20*). These tests were conducted well below 10 pct fracture toughness of WC-Co and PDC inserts, and damage to cutting edges is minimal, but obvious under microscopic examination.

## CONCLUSIONS

The following conclusions summarize the results of this experiment:

1. The penetration rate increased linearly with thrust. However, the thrust was limited to 15.88 kN, the test bolter's limit.
2. 30 to 40 L/min of waterflow at 554 kPa water pressure was found to be adequate for flushing out the cuttings, maintaining penetration rate, and keeping the bit tips cool. However, greater pressures are recommended as a safety precaution against fluctuations and sudden loss of line water pressures.
3. The roof bolter used was not capable of delivering more than 450 rpm, so the effects of increased revolution per minute remain unknown.
4. The wear mechanisms for WC-Co and PDC bits are quite different, and this difference is the primary cause of higher bit life for PDC inserts. Grain sizes and mounting configurations of WC-Co and PDC bits are different. It is believed that an increase in the angle of WC-Co inserts might prolong bit life in some coal mines, but this hypothesis remains to be tested in mines.
5. The cutting edge of a PDC bit remains relatively sharp throughout its life and any decrease in penetration rate is adjusted by corresponding decrease in bit diameter. The penetration rate does not vary greatly as the edge sharpness is decreased.

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# APPENDIX.—LITERATURE REVIEW

## HISTORY AND DEVELOPMENT OF SYNTHETIC DIAMONDS

At present, diamond is the hardest known naturally occurring material, which has made it an excellent source for manufacturing drill bits for the past 50 years. It has excellent thermoconductivity properties (*12-14*), produces little friction and, consequently, little heat when cutting through rocks.

Diamonds have been scarce for industrial use and attempts have been made to produce synthetic diamonds. The road to manufacturing synthetic diamonds was lengthy and complicated, but in 1953 there were significant breakthroughs. Scientists at Allemanna Svenska Elektrica A.B., General Electric Co. (GE), Soviet Academy of Sciences, University of Chicago, and Stanford University, all produced synthetic diamonds about the same time. In 1955, GE produced a single diamond crystal for commercial use at pressures and temperatures greater than 7,000 MPa and 1,200 °C. In 1974, a team of Russian scientists produced synthetic diamonds at atmospheric pressure by using methane (*21*), and in early 1980, the Japanese researchers and manufacturers successfully advanced the Soviet method with new techniques and revolutionized the production of synthetic diamonds at low pressure.

Since 1981, synthetic diamonds have been made from methane ($CH_4$), carbon monoxide (CO), and other hydrocarbons using chemical vapor deposition (CVD), plasma CVD, and numerous other methods. The Dupont Co. synthesized diamonds and diamond-like carbons from graphite using high-power explosives. The shock waves generated by the explosions create enormously high pressures for a very short period, causing graphite to change into diamond (*21*).

## USBM RESEARCH WITH PDC BITS

Since 1979, the USBM has been engaged in research to put PDC technology to use in the mining industry. Reports show that diamond-coated bits have the potential to reduce frictional ignition of methane in coal mines and enhance the life of coal-cutting tools (*9*). In-mine tests (*3-4*) demonstrated that when used per instructions, the PDC bits have a life span 200 to 600 times longer than conventional drill bits.

Laboratory research by the USBM's Twin Cities Research Center (TCRC) shows that WC-Co bits are capable of cutting through rock having a compressive strength of less than 117,211 kPa (*22*). This investigation was conducted without using water and at large depths of cut. Under these conditions, bits are more susceptible to thermal damage because of excessive thrust required by deeper cuts. For PDC bits, phase transformation takes place at 750 °C (*11*) whereby diamond is converted back to graphite. To overcome this obstacle for drilling applications, it is essential to maintain adequate water circulation around the bit tip, and limit thrust and revolution per minute of drill steels to avoid overheating of bit tip area in contact with rock surface. Under these conditions it may be possible to drill roof rock having a compressive strength of up to 206,843 kPa.

A new class of PDC and WC-Co bits was designed, fabricated, and tested at Sandia National Laboratory (*23*). The design configuration of these bits was similar to commercially produced auger bits, except the new bits used two 13-mm-diam disks as cutting edges and were mounted at a 20° angle to the cutting face. A series of tests were conducted in eight coal mines to verify laboratory results (*23*). At the first mine, 135 holes were drilled with a single PDC bit, while only one hole was drilled with a single WC-Co bit. Some minor changes were made in bit design and testing procedure, but after seven attempts in different mines they were unable to repeat the earlier results. The higher life for PDC bits was attributed to their superior design rather than to PDC's strength and hardness (*23*). In 1991, Brady Mining Tools revised the earlier PDC bit design, and this bit is now commercially available (*24*).

## BIT WEAR STUDIES

To date, no research has been conducted to determine what effect revolution per minute, thrust, and water pressure have on the life of roof-bolt drill bits. Therefore, pertinent literature on causes of wear of WC-Co mining bits has been reviewed to gain insight into failure mechanisms of roof-bolt drill bits.

An exhaustive review of various aspects of wear of coal-cutting tools was done by several universities and research organizations in the former Soviet Union (*25*). This research shows that rapid bit wear starts taking place whenever the temperature in the bit rock contact area reaches a critical point. This temperature depends on the thermophysical properties of alloys used, abrasion resistance of the material being cut, and machine parameters such as thrust, revolution per minute, penetration rate, and water pressure for cooling and cuttings removal. Bit wear is classified in three categories: fatigue, fatigue-abrasion, and abrasion.

An investigation was conducted on the effects of cutting speed, quartz content, and grain size on the life of steel bits (*26*). It was found that wear increased when the percentage of quartz and the cutting speed increased. The grain size and tensile strength of the rock also had some effect on bit life. Although unnoticed by Schimazek (*26*), the quartz content of the material being cut affects temperatures in the contact zone between the bit and the rock, causing steel bits to soften and wear more quickly (*4*). It has been reported that when the quartz content of roof rock reaches 30 pct, it drastically reduces bit life (*4, 27*).

The USBM determined the feasibility of using coal-cutting tools to excavate hard rock (*28*). When the cutting speed was increased from 25 to 177 cm/s, there was no significant increase in cutting efficiency. However, the higher speeds contributed to the rapid wear of WC-Co cutting tools. In conclusion, rapid bit wear in limestone and dolomite, which have compressive strengths of 117,211 and 206,843 kPa, respectively, precludes use of carbide-cutting tools.

Wear rate is also proportional to the hardness of the surface being worn (*28*). The frictional heating of the wear surface raises the bit temperature, thus decreasing hardness (*11, 29-30,*). Because there is large variation in the grit hardness of every sedimentary rock, it would be virtually impossible to apply the laws of friction (*22*) to rock and minerals (*31*). Hardness of WC-Co alloys falls slowly with increasing temperature, but after approximately 400 °C, decreases quickly (*11, 32*). At approximately 650 °C, the hardness of some grades of WC-Co alloys drops below the room temperature hardness of quartz, 9.83 to 11.3 GPa (*33*).

A phase transformation occurs at 573 °C, after which its hardness increases to 24.5 GPa (*33*). Room temperature hardness of WC-Co alloys ranges from 11 to 17 GPa. Many investigators have suggested that when the hardness of WC-Co alloys approaches 80 pct the hardness of quartz, increase in wear takes place (*19-20*). Cook (*34*) refers to temperature as "one of the most important tool-wear parameters." Tests were conducted in hard limestone and the results show that "the main agent of destruction of picks in hard rock is thermal stress" (*35*).

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